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THE TROTTER-PATERSON MEMORIAL LECTURE

The Interference of Waves

By SIR LAWRENCE BRAGG, F.R.S.

I am very grateful to you for your invitation to give the Trotter-Paterson Memorial Lecture in 1957. I have a personal reason for appreciating the invitation because Sir Clifford Paterson was a friend of long standing whose work I greatly admired. He had many links with the Royal Institution where we are meeting to-night.

The subject of my talk is the interference of waves. The Royal Institution is pre-eminently a place with a long tradition of discourses illustrated by experiments, and when I received your invitation I thought you might be interested in a series of demonstrations of interference effects. One of our main activities is a series of lectures, running throughout the school year, for boys and girls from the schools of Greater London, and the demonstrations I am going to show you are chosen from those which we show on these occasions. They are designed to illustrate fundamental principles and to familiarise the audience with the concepts of interference.

I could not make a more appropriate beginning than by reminding you of the first famous interference experiment which established the wave theory of light. Thomas Young was one of our first professors; he was elected Professor of Natural Philosophy and Chemistry in 1801. In 1807 he published his famous "Course of Lectures on Natural Philosophy and the Mechanical Arts." I am reproducing three figures from this volume with their explanations, and a quotation from the lectures.

> "Supposing the light of any given colour consist of undulations, of a given breadth, or of a given frequency, it follows that these undulations must be liable to those effects which we have already examined in the case of the waves of water, and the pulses of sound. It has been shown that two equal series of waves, proceeding from centres near each other, may be seen to destroy each other's effects at certain points, and at other points to redouble them; and the beating of two sounds has been explained from a similar interference. We are now to apply the same principles to the alternate union and extinction of colours."

You will remember that he allowed light which had passed through a narrow pin-hole to fall on two pin-holes close together, and found that a screen which received these two sets of waves was crossed by a series of fringes which he ascribed to their interference. Young explained the origin of these interference fringes with his ripple tank in which waves on the surface of water from two sources were made to interfere (see his Fig. 265). We have Young's original ripple tank, and it is displayed for you to see in the ante-room. It is more convenient to demonstrate the effect in the lecture theatre with a small tank, the ripples being projected on to the screen. A prong attached to a vibrating fork dipping into the liquid creates the waves. We can either have one prong and pass the waves through two slits, or have a double prong which sets up two wave trains. In both cases the waves build up into a large amplitude where the crests and troughs coincide and cancel each other where the crest of the first set coincides with the trough of the other. When showing Young's phenomenon with light, it is simpler to increase the intensity by using slits instead of pin-holes; it is easy to reproduce the effect on the optical bench but it is not an experiment which can be conveniently demonstrated to a large audience.

Young's experiment is so simple an example of interference that it is generally

The fourth Trotter-Paterson Memorial Lecture delivered at the Royal Institution, London, on February 11, 1957.

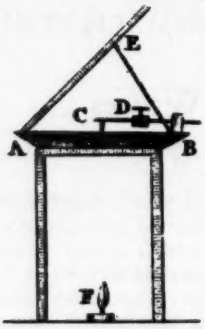

Fig. 265

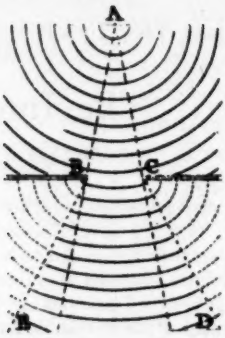

Fig. 266

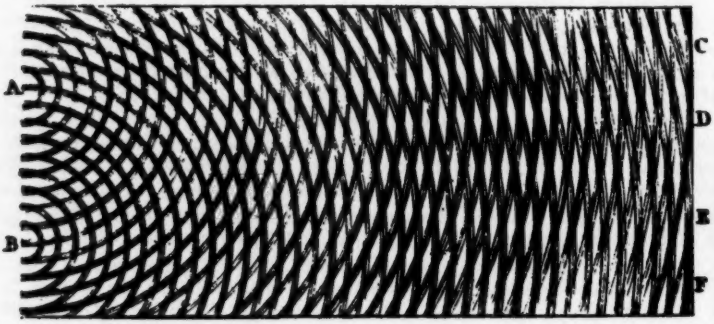

Fig. 267

Three figures from Thomas Young's "Course of Lectures on Natural Philosophy and the Mechanical Arts" (1807).

Fig. 265. An apparatus for observing the motions of waves excited, in a fluid poured into the trough AB, by the vibrations of the elastic wire C, loaded with a movable weight D; the shadow of the waves being thrown on a screen E by the lamp F, through the bottom of the trough, which is of glass.
Fig. 266. A series of waves, diverging from the centre A, and passing through the aperture BC, extend themselves on each side so as to fill the space BCDE, while they affect the parts without this space much less sensibly.
Fig. 267. Two equal series of waves, diverging from the centres A and B, and crossing each other in such a manner that, in the lines tending towards C, D, E, and F, they counteract each other's effects, and the water remains nearly smooth, while in the intermediate spaces it is agitated.

the first to be described to the student of optics. But it is, perhaps, worth while going into it a little more thoroughly and considering exactly what it proves. How small must the first pin-hole be, and what angle should be subtended at the first pin-hole by the next pair, in order that the experiment may succeed? The wave-length of light is very short, and small though the pin-hole be, it is obviously very large compared with the wave-length. It does not emit a single series of waves like the prong on the tuning fork. Instead it is covered by a complex ether storm of all amplitudes and phases coming from the sodium flame or other source of light

behind the pin-hole. Let us call the first pin-hole P and the next pair A and B as in Young's figure. A receives wavelets from all over P and, depending on their amplitudes and phases, they build up vectorially into a resultant wave. If now we pass to B, the wavelets from the different parts of P, with different path lengths as compared with A, must have a somewhat different resultant. But if B is so close to A and P is so narrow that these changes in path length are small compared with the wavelength of light, the net result at B will be extremely similar to that at A. The waves issuing from A and B are, therefore, closely related in phase and amplitude and so they interfere like those produced by the two prongs on the tuning fork. They are, as we say, coherent. If we make P too large or separate A and B by too great

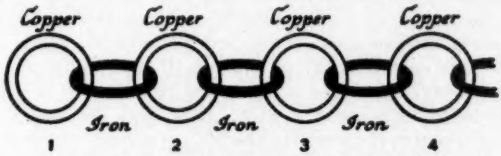

Diagram to illustrate the nature of electromagnetic waves.

an interval, this coherence is lost and the interference fringes are so constantly and repeatedly changing their position that they can no longer be seen.

The point to note is that Young's experiment depends on geometrical factors such as the dimensions of the pin-holes; it does not tell us, for instance, whether light is only coherent when it comes from the same sodium atom in the flame. All we can say is that we can prophesy successfully what we ought to observe with a given geometrical disposition by assuming light to behave like waves; it is important to realise this when the quantum theory aspects of light are being considered.

Another attractive illustration of Young's interference principles is afforded by short sound waves. Ordinary sound waves, several feet in length, are on too large a scale for us to do interference experiments in the lecture theatre. But this small electro-magnetic emitter, pitched almost beyond the audible range, gives us waves of a few centimetres in length. They can be detected by the sensitive flame, a gas jet in which the pressure is such that it is almost on the point of becoming unstable and roaring. Such a jet as you see is very sensitive to any high pitched sound such as the rattling of keys or the squeaking of a glass stopper in a bottle. It dips when it receives the sound. When a train of waves falls normally on a reflecting surface, the reflected train interferes with the incident train and produces a set of standing waves. These standing waves are illustrated rather prettily by the Vinycomb model of wave motion which I can demonstrate to you. I set a train of waves going in this system of laths supported by two springs near their centres. The last lath is clamped in position, so that the waves are reflected to the far end of the model and you will see these standing waves strikingly demonstrated. The same thing happens in the air. If I reflect the short sound waves by a glass plate behind the sensitive flame, you will see the flame duck and rise as I move the plate backwards and forwards and so displace the system of nodes and loops through the position of the flame.

To pass now to electro-magnetic waves—young people find it very hard to get their first grasp of the idea of an electro-magnetic wave. This is not surprising; I imagine that when Maxwell first put forward the conception, there can have been very few people in the world who realised what he was driving at. A changing magnetic field sets up electrical tensions in its neighbourhood. In turn changes in the electrical field set up magnetic fields in neighbouring space. Therefore rapid alternations of electrical field produce magnetic fields which in their turn produce electrical fields and so on; so that the disturbance spreads out as a wave, just as the electrons

rushing up and down the aerial of a radio transmitter station send out the disturbances which are picked up by our aerials and radio sets. Now this conception is literally very much in the air, and we can make it clear to the beginner by associating solid matter with it. The accompanying diagram shows a series of linked copper rings and iron rings. Start an alternating current round the first copper ring. It will magnetise first in one direction and then in the other, the iron ring linked with it. By Faraday's principle of induction, this changing magnetisation produces surges of current in ring No. 2 which will in turn magnetise the next iron ring and so on. Here we see it done experimentally. I have a series of rings made of conductors and of iron. I can rattle them about to show that they are quite independent of each other, but you will see that if we pass an alternating current round the first conducting ring, a lamp connected to the last will light up. Now we can proceed in our imagination to take the copper and the iron away. Taking the iron away is easy, everyone knows that a magnetic field can exist in free space quite independently of any iron. It is not quite so easy to see that we can take the copper away. But what is an electric current? It is a number of charges attached to electrons running along a wire. How does the iron know, so to speak, that an electron is moving in the neighbourhood? It can only be because it experiences a change in the electric field due to the motion of the electron. So we get the idea, which was Maxwell's great contribution, that a change in an electrical field is equivalent to a current and the electro-magnetic theory of light follows.

The most beautiful interference experiments are seen with light, but they are not easy to show to an audience because of their small scale, the wave-length of light being only about 6.10^{-5} cm. I have an apparatus here with which we can demonstrate all the well-known interference effects with electro-magnetic waves just under a centimetre in wave-length. We owe this apparatus, which is extremely valuable for demonstrations, to the kindness of Messrs. Marconi who presented it to us for our school lectures. The Klystron produces waves of 0.87 cm. in length. They can be picked up by this detector which has an indicator lamp on it which lights up when they are being received, and also is connected to a loud-speaker so that you can judge the intensity of the received waves by the loudness of the sound. I shall first show a series of simple experiments to illustrate that these waves behave like light. You will see the lamp light up and hear the sound when I place the receiver in front of the emitter at a distance of some six feet. If I interpose a slab of paraffin wax several inches thick, the sound is still there, showing that the waves go through the slab of dielectric though some intensity is lost by reflection and absorption. A metal plate completely stops the rays. They are reflected by the metal plate, as we can see by searching with the detector for the reflected beam. A concave metal mirror brings them to a focus. A large paraffin prism refracts them to one side. Finally here is a rather pretty experiment. You probably know those table lamps where a light in the base is, so to speak, "piped" along a tube of transparent plastic, curved in any way, because it is totally reflected internally. I have here a long rod of solid dielectric, one end of which I place in front of the emitter. In whatever direction I point the rod, the energy is found at the far end when I hold the receiver there. A lens of plastic focuses the waves like an optical lens. Here is another kind of lens made of wave guide tubes. The wave-length in such a wave guide is greater than that in free space. Hence a regular wave train appears to travel faster than light in such a tube. This is of course only true of its wave velocity, not of its group velocity, so we are not finding any phenomenon which would have caused Einstein concern. Since wave guides behave in this way, the waves are converged by a lens which looks as if it ought to produce a diverging effect. This lens made of tubes side by side is thinnest in the middle and thickest at the periphery.

It is possible to reproduce Young's classical experiment by passing the waves

through these two slits. You will see that if we cover up the one or the other, the receiver picks up waves uniformly over a large arc. If both are uncovered, however, we pass through a series of fringes shown by fluctuations of the light from the lamp and the sound. Now I shall reflect these waves from a plain metal surface and search for the standing waves. This needs a steady hand for they are only about half a centimetre apart. If however I run through them rather quickly, I think you can hear the purring sound from the loud-speaker. Here is a demonstration of the Lloyd's mirror experiment. Waves fall very obliquely on a long plane mirror and we get interference between the direct and reflected beam. Another somewhat similar experiment depends on the use of a so-called "split mirror." One half of a plane mirror can be displaced backwards or forwards in relation to the other half. When the two halves are coplanar, reflection takes place as by a single mirror. By moving one half forward, we can destroy this reflected beam by interference, but the energy appears in two new beams one on either side of the original position.

I will now use the same apparatus to demonstrate the way in which electromagnetic waves are diffracted by a regular pattern in three dimensions. This, may I remind you, is the basis of the determination of crystal structure by X-rays. The atoms in a crystal are arranged on a regular pattern, the dimensions of this pattern being several times as great as the length of the electro-magnetic waves which constitute X-rays. Conditions are therefore right for observing interference effects. By measuring these effects, we can determine the arrangement of the atoms and studies of this kind have led to great advances in our understanding of the properties of matter.

It is always difficult to think in three dimensions. It is perhaps easier to grasp the nature of the interference effects produced by crystals if we think of the atoms in the crystals as being arranged on parallel sheets in a number of different ways. We are familiar with the interference effects produced by these parallel sheets. The colours of a soap bubble, or of an oil film on water, are examples of interference produced by a single thin film. If there are many parallel sheets, the colours become brighter and purer as in opal and mother-of-pearl. We get a strong reflection when the waves reflected by successive planes are in phase, a weak reflection when they are out of phase, depending upon the wave-length of light, the angle of incidence, and the spacing of the planes. As a crystal is turned round in an X-ray beam, successive planes in turn come into the reflecting position and if the condition for interference is satisfied we get a strong diffracted beam. Here is a model of a crystal in two dimensions, with thin metal rods about a centimetre and a half apart, set parallel to each other in a regular pattern. We are going to make it rotate in the beam from the Klystron. We set a receiver, like the telescope on a spectrometer, at a predetermined angle which is correct for a diffracted beam from the crystal. You will see that as the turning crystal model passes through the diffracting position, a strong beam is received. It can be seen on this cathode ray tube. A bright spot on the tube is displaced from the centre by an amount corresponding to the intensity of the received beam. By means of a servo mechanism it is possible to arrange that the direction in which it is displaced rotates with the rotation of the crystal. This crystal model comes into the reflecting position four times during each rotation, and so it draws what looks like a flower with four petals on the screen of the oscillograph. Here is a more complicated type of diffraction, with many sets of planes coming into the right orientation in each revolution and a daisy with many petals appears on the screen.

Finally, if you think my examples are too elementary and wish to make some mental effort more worthy of your powers, here is a really complex example of diffraction. I have a model in front of me of what we call a precession camera for measuring and indexing the X-ray beams diffracted by crystals. It is of a type invented by M. J. Buerger in the United States. The diffractions are a three-dimensional complex. The orders of the spectra from a line grating can be called 1, 2, 3, etc., depending on the

number of wave-lengths of path difference between one line and the next. An order of diffraction from a crystal must be given three indices, hkl. If we do not go further than the tenth order, there are 1,000 of them. So you will realise that the geometry of the problem becomes a good deal more complex. This apparatus which I can set working here twists the crystal, the transmitting aperture, and the receiving photographic plate, in a complicated kind of interweaving dance. The net result is a regular array of diffracted spots on the plate which can be measured and indexed with ease. I shall try to show you by the aid of the model how this result is achieved.

One can perhaps say that in the X-ray analysis of crystals, interference principles have been developed to a greater extent than in any other branch of science, but they are the same principles whether they apply to ripples of water, sound waves in the air, or electro-magnetic waves of all ranges between radio and X-rays.

Vote of Thanks

DR. W. S. STILES (proposing): One of the pleasant circumstances of our Trotter-Paterson Memorial Lecture is that, thanks to the kindness of the Managers of the Royal Institution, we have our meeting in this historic lecture theatre. This afternoon we have not only had our lecture here but—much more—we have had, in Sir Lawrence Bragg, the *genius loci* to give it. What an engrossing lecture, beautifully illustrated with experiments, we have had. I hardly need recall that Sir Lawrence's fame as a man of Science is supplemented by his reputation for making difficult things simple. In expressing our warm thanks to him for this lecture we cannot pay a higher tribute than to say we have been delighted by both matter and manner—just as we expected to be.

I had the good fortune to study physics under another famous physicist with the faculty of making hard science simple. I mean Sir Lawrence's father, Sir William Bragg. I remember in one of our professors' early lectures he explained a point in some such words as these: "The electron must go *there* for how could it possibly know which of the other alternative places it ought to go to." We were serious youths and this seemed rather frivolous reasoning to establish the mode of action of one of the two fundamental particles of matter—there were only two in those good old days. Of course, it was later borne in on us that all the best reasoning in physics was of this simple kind. This afternoon we have seen such methods in action. Sir Lawrence has brought us into contact with some essential notions of science in a way we can understand and has delighted us in the process.

Many years ago Sir Lawrence was Director of the National Physical Laboratory for a time—an all-too-short time we thought—before removing to the more rarefied atmosphere of the Cavendish Laboratories. It is a particular pleasure to me to move this vote of thanks to my former chief for his admirable lecture.

DR. J. N. ALDINGTON (seconding): I think the most important impression which has been left in my mind, and I am sure, Mr. President, in that of all the members this evening, is the sense of privilege and the sense of occasion as we listened to the discourse and witnessed the beautiful experiments of Sir Lawrence Bragg.

You will recall that a few minutes ago Sir Lawrence produced for us in a deceptively simple manner the derivation of the Bragg Law, and told us that nowadays any sixth-former apparently would be able to derive such a conclusion with ease. I am quite sure that on this point members of the Society will agree with me, and profoundly disagree with Sir Lawrence, in reaching the conclusion that if that was sixth-form work, we must still be in the second form!

As I watched the fascinating series of demonstrations which Sir Lawrence has provided for our enjoyment and instruction, I was impressed by a certain type of remark which he made on several occasions. I wrote one or two of them down:

Sir Lawrence said at a certain stage in his discourse, " It takes a little thinking about," and then a little later he said again, " It takes a little more thinking about." Towards the end, as we were led through the complexities of crystal structure analysis, Sir Lawrence completed a particularly interesting section of his address by saying " if we try and think about this."

I want to suggest that that thought has been behind all the notable contributions to science which Sir Lawrence has made and is the major lesson which we can learn from this evening's meeting. By thinking about the results of experiments and by devising new experiments Sir Lawrence has, among other things, given precision to our picture of the solid state.

It must have been a great moment when, through his interpretations of X-ray diffraction patterns, he was able to show the cubic structure of sodium chloride and even more exciting than this was the confirmation by his demonstration of the tetrahedral structure of the diamond that the organic chemists were right in their conception of the normal linkages of the carbon atom.

We have been greatly impressed this evening, Sir Lawrence, by the simple way in which you have unfolded to us the techniques by which these mysteries have become no longer mysterious, and many of us have followed with admiration your present work which, by advanced application of these same techniques, is gradually unfolding the structure of the protein molecule with its great complexity and its thousands of atoms.

Mr. President, I began by speaking of the sense of privilege which we have all felt on this occasion. We shall be long inspired as we think back to Sir Lawrence's memorable contribution to our series of Trotter-Paterson Memorial Lectures.

Artificial Lighting as an Effective Aid to Architecture

By H. E. BELLCHAMBERS, A.M.I.E.E. *(Member)*; R. V. MILLS, A.M.I.E.E. *(Member)* and H. R. RUFF, B.Sc., M.I.E.E. *(Member)*

Summary

From an analysis of that part of the architect's task, the lighting of buildings, a method is developed whereby the architect and lighting engineer can co-operate to solve the problems involved in the translation of an artistic conception into a satisfying installation.

The method of deducing the required brightness pattern, and of achieving this, is illustrated by following its practical application, using, as a simple example, the lighting of an entrance hall.

(1) Introduction

Architecture could, perhaps, be described as the art and science of enclosing space for human activities usefully and graciously.

Enclosing of space introduces problems of heating, ventilation, and detailed planning of the building for its particular function. This occupies much of the architect's effort; but unless light, both natural and artificial, is skilfully directed, unnecessary difficulties will be introduced into the activities for which the building was designed and it will not be possible to appreciate its architectural features.

Much painstaking work has enabled light intensities, colours and luminances to be measured. The Society has encouraged the integration of the experience of lighting engineers, and from measurements made in installations it has been possible to draw up codes of good lighting practice, covering a wide range of activities to give guidance for lighting schemes. The code is generally based upon light intensities required to give satisfactory conditions for generally accepted schemes of decoration. The recent work of the National Illumination Committee has been concerned with possible methods for designing to give a required brightness pattern.

Much interesting work is being undertaken internationally to help determine acceptable brightness ratios. There is often some degree of conflict between the uniformity of lighting desirable to give easy visibility for the task, and the introduction of effective contrasts to produce interest and individuality into a building.

It seems that many of the lighting effects that architects would like to produce stem from some of the beautiful natural scenes in sunlight. Very great contrasts can sometimes produce beautiful patterns; but patterns, even in natural lighting, should be considered in conjunction with the tasks to be performed.

Fig. 1 shows a louvre system which serves to prevent dazzle from natural sunlight. The supporting members produce an interesting pattern on a plain concrete path. The pattern is small, makes the scene much more interesting and does not affect the use of the path.

In Fig. 2 quite an interesting pattern is produced by the sunlight streaming through the windows. In this case, however, the pattern is superimposed on a stairway and could be confusing to the safe use of that stairway.

To some extent the first pattern leads along the path : architects are often able to use light patterns for guidance, and these are more definitely under their control when the lighting is artificial.

Apart from patterns which can be introduced by different light intensities, architectural patterns and textures must be revealed by the lighting. A room with a

The authors are with the Research Laboratories of the B.T.H. Co., Ltd., Rugby. The paper was first received on November 21, 1956, and in final form on December 13, 1956.

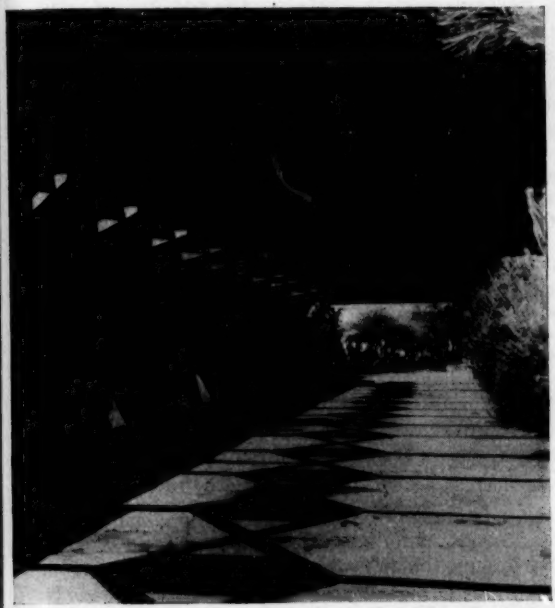

Fig. 1. Contrasts in light and shade producing an interesting pattern and aiding movement along the walkway.

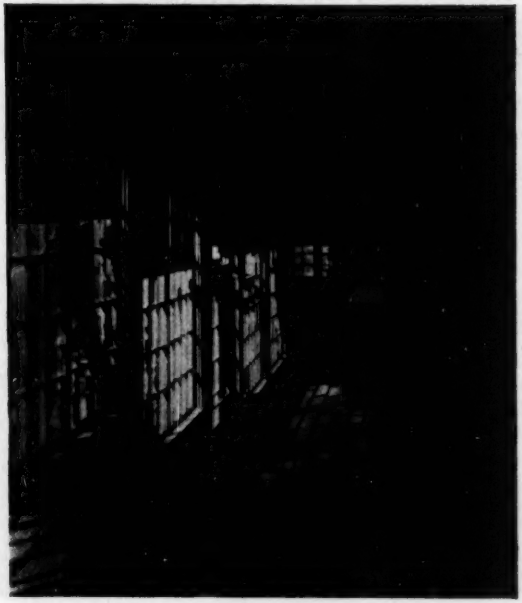

Fig. 2. Contrasts in light and shade thrown across a stairway introducing a distracting effect which may be the cause of accidents.

single main theme is shown in Fig. 3—a bank requiring good lighting both for clients and at each clerk's desk and till. The simple module lighting panel scheme is dependent for its success on the reflectivities of the whole decorative scheme. The light surfaces, particularly of the floor and walls, give sufficient upward light to prevent glare from the lighting panels. The uniform illumination, though good for the task, could be monotonous, but this is prevented by the pleasing architectural scheme and the texture of the materials used.

It is now generally accepted that it is important for the architect and lighting engineer to get together at a very early stage to ensure that the lighting produces the effect envisaged by the former.

Following a brief review of the basic tools, the light sources and problems of installing them, the main paper describes some of the major problems involved in the translation of an artistic conception of a building into a satisfying installation, through the interpretation of a brightness and colour pattern into light intensities and colour values that can be calculated and measured to ensure that conditions are satisfactory for the activities concerned, while giving pleasant individuality to that building.

(2) Light Source Features

As far as the architect is concerned the light source consists of a lamp in its luminaire. It is useful to summarise some of the main features to assist his choice.

(2.1) Lamps

There is now a mass of information on lamps available from manufacturers' catalogues, handbooks and specifications, and a complete picture of world progress in electric lamps is contained in the Compte Rendu of the C.I.E. Light Source Committee reports([1]).

Whilst detailed information can be obtained from these, a summary of the main characteristics of sources used for interior lighting—incandescent filament, fluorescent and mercury vapour—has been prepared as Fig 4. Column 4 gives a picture of the relative power required to obtain a given intensity of lighting from the different sources;

Fig. 3. An example of a lighting installation with a single, simple theme.

with modern high lighting intensities, particularly those used in America, this total power must be considered in conjunction with heating and ventilation plants.

In column 7 a greatly simplified approximation has been introduced to denote the colour rendering of the sources relative to natural daylight. The distortion of colours by incandescent lighting is generally realised and accepted, and such acceptance has now in general been extended to cover the standardised fluorescent lamp colours. In many artificial lighting schemes the use of the fluorescent lamp for general lighting, and incandescent sources for high-lighting, is standard practice. From user demands for the various lamp colours it appears that the higher efficiency of the sources giving reasonable colour rendering, Daylight and Warm White, is preferred to the better

TYPE OF SOURCE	RANGE OF POWER (WATTS)	REPRESENTATIVE LUMINOUS EFFICIENCY (LUMENS /WATT)	RATIO OF POWER FOR EQUAL LIGHT FLUORESCENT=1	NOMINAL LUMINANCE CANDELAS/□"	POLAR CURVE SHAPES	EFFECT ON COLOURS * (RELATIVE TO NATURAL DAYLIGHT) BLUE	GREEN	YELLOW	ORANGE	RED
INCANDESCENT FILAMENT										
CLEAR	15-10,000			6,500						
PEARL.	15 – 200			50						
SILICA COATED	40 – 200	12	4	16		A	A	B	C	C
REFLECTOR SPOT	75 – 250			130 BEAM AVERAGE						
REFLECTOR FLOOD	75 – 250			30						
LIGHT TUBE	35 – 150	7	7	3						
FLUORESCENT – MCF										
COLOUR MATCHING	6-125	50	1	5		B	B	B	B	A
DAYLIGHT						A	B	B	B	A
NATURAL						A	A	B	B	B
WARM WHITE						A	A	B	C	B
DE LUXE WARM WHITE						A	A	B	C	C
HIGH PRESSURE MERCURY										
MA and MB	40-2,500	40	1·25	1,000		D	D	D	A	A
FLUORESCENT MBF	125-1,000			100		A	B	D	B	B

*COLOUR-EFFECT CODE: A=DEPRESSED; B= SIMILAR; C=ENHANCED; D=EXAGGERATED.

Fig. 4. Light source features.

colour rendering of the de Luxe colours, excepting for special conditions such as restaurants. Whilst appreciation of improved colour rendering will probably increase, at higher lighting intensities there seems to be less concern about small improvements.

Mercury vapour lamps are mainly restricted to certain industrial conditions, although the colour rendering is greatly improved in the modern fluorescent high pressure mercury lamps.

The simplest and most versatile electric lamp is still the filament lamp, and since these factors are often the foremost consideration it is the first choice for many applications. The architectural tubular lamp is for this reason used for some decorative effects, but for general lighting from linear sources the fluorescent lamp is now the automatic choice, requiring only one seventh the power, and giving a choice of colours. The introduction of instant starting circuits has made their response to switching similar to that of filament lamps.

It is most important in any installation to consider ease of cleaning and lamp replacement.

(2.2) Luminaires

The distribution of intensity from light sources is not generally suitable for direct application, i.e., without some means of control. The form which this light control will take will depend upon the purpose, but will generally be a redirection of light and/or a reduction of the source luminance. Sometimes, as in the case of the silica coated lamp and internal reflector lamp, some control is integral with the lamp.

It is usual to classify the light distribution according to the kind of illumination produced. There are six basic types and for convenient reference they are described in Fig 5. These various types of light distribution can be obtained using either point, linear, or area sources. Light control inevitably results in some losses by absorption and it is the lighting equipment designer's task to keep losses as low as possible.

For economic reasons luminaires have developed into a number of standard types

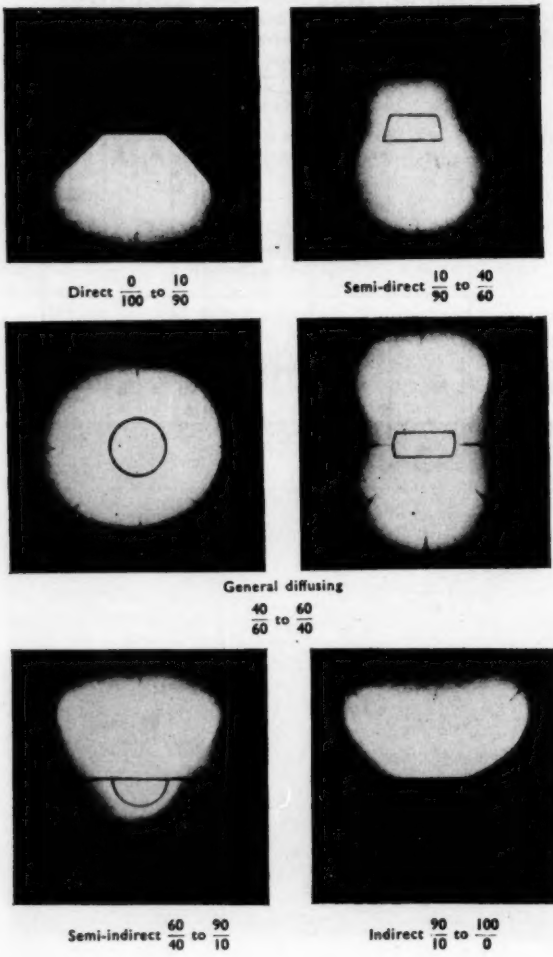

Fig. 5. Typical lighting systems.

whose purpose is easily specified. They have been evolved from experience, in many cases from trial and error methods of application, and good lighting practice has developed around them.

Trends in architecture are towards the greater use of elements of standard form which can be economically produced by industry. The form of these standard elements is influenced considerably by architectural needs, but must be based upon sound engineering practice. This applies to lighting as much as to all other building elements, and the architect's interest and influences are becoming increasingly effective[2].

There are, however, cases in which specially designed equipment is necessary if the architect's requirements are to be fully met. Inevitably this latter type is more costly to produce and often to install than the standard form.

(3) Design of the Visual Field

When an architect begins to plan a building he will be stimulated by two major considerations which are closely inter-related. One is humanistic, the other structural.

In designing for the visual field the architect should have these two major considerations very much in mind. In a preliminary specification they may, for convenience, be considered separately and later related as the general plan for the building develops.

The basis of the specification can therefore be dealt with initially from a consideration of:—

(a) The purpose of the building, its relationship to the people who will use it and the way in which it will be used.

(b) The building itself; the expression of the impact of its purpose on the mind and imagination of the architect, i.e., the character of the interior.

The purpose, whether it be factory, office, theatre, cinema, school or church, will be governed by a client's own special needs, and the purpose will have to be analysed before the lighting requirements can be specified.

The analysis will include: the nature of the room activities and any tasks that are to be performed, the degree of concentration, the degree of visual comfort and performance, contrast sensitivity, movement, time of operation, relaxation, and the relationship between the room and other parts of the building.

The lighting for the structural element in the plan, the character in the room, will include modelling and shadows, the flow and direction of light, accent, contrasts, the revealing of form and texture, the division of structural surfaces, and colour.

(3.1) Preliminary Specification

The architect will usually be designing for day-lighting as well as for artificial lighting, and the two must conform, in so far as the surface colours and reflection factors will be common to both.

The artificial lighting, to which this paper is restricted, need not follow the pattern of the day-lighting and sometimes should introduce a distinct change in the appearance of the interior.

When the architect has marshalled all the information he needs for the planning of the interior lighting and has formed the general outline of his "solution," then the lighting engineer can consider the means to achieve the desired end.

From the basic specification approximate values of illumination levels for general and for special purposes can be noted. From these, values of luminance for the overall environmental brightness pattern, for particular surfaces, and for the order of contrasts and surface reflection factors, can be suggested; and the type and form of luminaire preferred by the architect considered.

The preparation of a preliminary and the final specifications can be aided by the use of perspective drawings showing the main structural outlines and contents of the

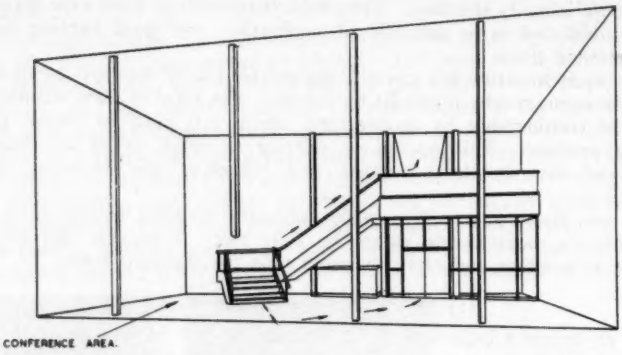

Fig. 6. Entrance hall, perspective outlines for a preliminary specification.

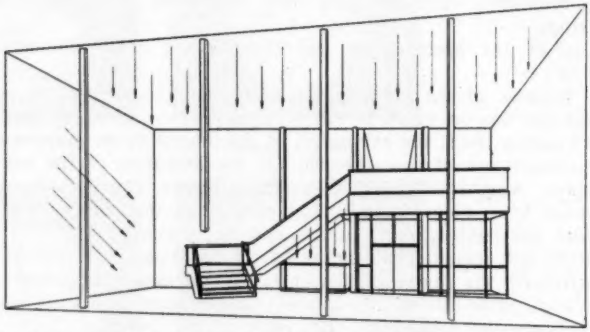

Fig. 7. Entrance hall, perspective for first stage of specification showing flow and direction of light.

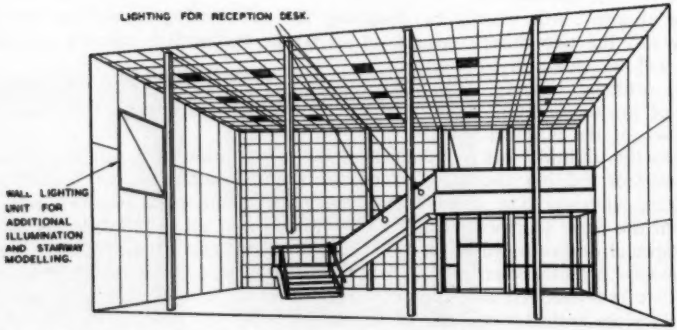

Fig. 8. Entrance hall, perspective, summarising the main lighting scheme, surface textures and luminance.

Table 1
Basic Data Required for Designing Lighting for Visual Comfort and Efficiency.

GROUP 1 Item No.	DATA REQUIRED	EXAMPLE

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Table 1

GROUP 1 — **Basic Data Required for Designing Lighting for Visual Comfort and Efficiency.**

Item No.	DATA REQUIRED	EXAMPLE
1	Purpose of building	Entrance hall large office block
2	Size of room	Length 48 ft. Width 30 ft. Height 24 ft.
3	Main purpose of room	Entrance to offices ground and first floors. Reception and routing of visitors. Area for waiting and interviews or exhibition area.
4	Main contents of room	Large stairway, reception desk, small table and chairs.
5	Primary tasks	Movement through hall to ground and first floor offices.
	Size, Contrast, Standard of performance	Not critical
	Minimum illumination	7 lm/ft².
6	Secondary tasks	Reading and writing at reception desk and small table.
	Size	Large to small
	Contrast	V. good
	Standard of performance	No sustained effort required
	Minimum illumination	10 lm/ft².
		Based on I.E.S. Code
7	Desired standard of visual comfort	"Just acceptable" K = 120
	Observation point	At entrance door, 5 ft. 6 in. above floor level
		Based on B.R.S. Criteria.
8	Adaptation level (weighted average general surround luminance)	5 ft. lamberts
9	Task to background contrast grading	Not greater than 10 : 1 at reception desk, 30 : 1 elsewhere.
10	Movement through room	See 5 above.
11	Times room is in use	8 a.m. to 6 p.m.
12	Relaxation needs (Visual rest centres)	Not important if item 7 is satisfied.
13	Preferred colour appearance of room	Warm.
14	Colour rendering	Not critical but must be attractive.
15	Surface reflection factors (preliminary)	Walls—North 70 per cent. East and West 40 per cent. Ceiling—80 per cent. Floor—30 per cent.

Table II

GROUP II **Basic Data Required for Designing Lighting for Room Character.**

Item No.	DATA REQUIRED	EXAMPLE
1	General direction and flow of light	Mainly from luminaires located in ceiling with additional light directed mainly downwards at approximately 45 deg. angle to the vertical and 30 deg. to the horizontal. The latter to be provided by a wall unit located on the west wall directing light towards the north wall.
2	Index of modelling	On stairway (*a*) in azimuth 4 : 1 (*b*) in altitude 6 : 1 Other positions (*a*) in azimuth 3 : 1 (*b*) in altitude 4 : 1
3	Contrasts and divisions between main structural surfaces	To be obtained by materials used for surface finishes, i.e., light, high reflecting north wall contrasting with lower reflectivity east and west walls. Upward light if required to adjust contrast between luminaire and ceiling.
4	Luminance of areas of special interest	Reception desk top—12 ft.-lamberts on white paper. Conference area tables—12 ft.-lamberts on white paper.
5	Luminance of surfaces serving as visual rest centres	See item 12, group I.
6	Texture of main surfaces	North wall—Rough texture. East and west wall—Smooth surface natural wood finish. South wall—All glass. Floor—Lino tiles. Ceiling—Acoustic tiles. Stairway—Aluminium hand rail, glazed side panels.
7	Surface reflection factors	See item 15, group I.
8	Surface colours (preliminary)	North wall 100 y.r. 9/2. East and west wall 7.5 y.r. 6/6. Floor to be chosen later (Munsell notation).
9	Type of luminaire	Recessed module 24 in. × 24 in. preferred.
10	Location of luminaires	In ceiling symmetrical layout preferred by architects.
11	Additional notes	Entrance Hall. Canopy over drive in road to be lighted by luminaires recessed in canopy. Illumination progressively increasing towards entrance door.

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room. Designers will develop their own form and method of recording specification data as each stage in the design is reached. The diagrams in Figs. 6, 7 and 8 and the associated Tables I and II are possible forms related to an Entrance Hall, used as a simple example.

The information supplied by the architect will indicate the most important part of the design; whether some specific task has to be performed or activity carried on, whether the humanistic or structural element predominates. Whichever this may be, it should be dealt with first and the other held subordinate although closely linked. The humanistic aspect will be considered first because this will as a rule be the more important.

(3.1.1) *Visual Task*

From the analysis of the purpose of the building, the relative degrees of importance of visual comfort and visual performance can be decided, followed by the extent of the luminance grading outward from the task and from the sources to fulfil these conditions[3]. The contrast necessary for good visual acuity and the luminance values for high contrast sensitivity at the task can then be added[4] [5].

In modern installations the limiting conditions of visual acuity and contrast sensitivity are not generally met, but these points may need attention in some designs where there are especially difficult tasks to be carried out.

To complete this part of the specification of requirements for the task, an appropriate adaptation level should be fixed. This will determine the mean value of the environmental luminance pattern.

Within the framework of this pattern, tasks subsidiary to the main task can be considered and any modifications that are deemed necessary can be made to values already chosen.

Table I lists the items to be determined for the first part of the specification and Fig. 6 is a perspective drawing used for this stage of the work.

(3.1.2) *Character of Interior*

This part of the specification may present greater difficulties than the first but, from the architect's basic requirements, the desired modelling and shadow can be assessed. The general flow and direction of light needed to reveal form and texture of objects and surfaces, and the division of structural surfaces, can be noted. A preliminary selection of surface colours can also be made.

The data required for the second stage in the preparation of the specification are given in Table II and Fig. 7. Luminance values can be added to the perspective drawing and the direction of light indicated. The relative quantities of direct and indirect light flux required to give the desired degree of modelling can be noted. These values will be selected so that they combine with those already chosen in section 3.1.1, to provide the right degrees of contrast while ensuring that the basic requirements have not been materially changed. The form and location of luminaires can then be added to the diagram and data summarised as in Table II and Fig. 8.

This work will involve the determination of a number of factors which are not generally arrived at easily and quickly. These are discussed in the following two sections.

(4) Luminaire Considerations

When selecting or designing luminaires and calculating the illumination that they will provide at any point in a room, it is necessary to be able to separate the direct from the indirect illumination.

(4.1) Direct Illumination

The method of calculating the direct illumination from luminaires will depend upon the relative sizes of the room and the luminaires and the light distribution from

them. They may have to be considered either as point, linear or area sources, and the method of calculation chosen accordingly.

Methods dealing with each type have been developed and are available in text books and papers. Many of these methods would be more widely used if they were prepared in the form of slide rules, protractors, nomograms, tables, charts or graphs allowing calculations to be made quickly and easily.

The direct light flux from all luminaires reaching each room surface separately must be determined. For point sources this can be obtained by using sinusoidal projection (onion diagram) or semi-sinusoidal (cylindrical) projection diagrams. For linear sources the "Sector Flux"(6) (17) method can be used, and for large area diffuse sources the method given by Moon and Spencer(7) using "flux functions" can be employed or the "P" charts developed by Zijl(8) are easily and quickly applied.

(4.2) Indirect Illumination

The considerable interest in the effect of the indirect component in lighting design is shown by the number of papers dealing wholly or in part with the subject which has been published in the past three years, and no doubt further papers can be expected. No single method has yet found complete acceptance, but the designer will select whichever method he may find suitable or convenient for his particular purpose and for the degree of accuracy he requires.

Moon and Spencer(9) prepared comprehensive tables from a mathematical consideration of the problem. These tables enable the total illumination including interreflections to be derived for various surfaces; there are, however, practical difficulties in applying them. Although by this method the final average brightness of a surface can be obtained if the direct illumination falling upon it is known, the reverse procedure, i.e., the determination of the direct illumination necessary to produce a specified final luminance, is complex.

Means for overcoming the defects of this method have been suggested by Croft(10) who uses "surface distribution factors" and by Phillips(11) using "flux functions" to simplify the calculations.

Waldram(12) has suggested that the indirect component can be determined with sufficient accuracy for practical purposes by considering each room surface as a large area diffuse source. Since the final luminance of each surface has been fixed, it is a simple matter to calculate the illumination each surface will contribute to the illumination at any point in the room. The sum of these illuminations from each surface is taken as the indirect component.

Hopkinson(13) has suggested a further method which has developed from studies of day-lighting design. The basis of the method is to split the total flux into two components, one of which is reflected first from the upper parts of the walls and ceiling, the other from the lower parts of the walls, and the floor. The indirect illumination at any part of the room is then found by the following formula

$$\text{Indirect illumination} = \frac{\text{Total first reflected flux}}{A(1-R)} \text{ lm/ft}^2$$

where A is the total area in sq. ft. of all the surfaces in the room and R is the average reflection factor.

The method used by Bellchambers and Ackerman(17) is to measure the ratio of total to direct illumination using models in which a variety of room proportions, surface reflection factors and light distributions can be introduced.

The methods suggested by Waldram, by Bellchambers and Ackerman, and by Phillips have the advantage that the indirect component can be determined from specified surface luminance values. The direct flux to each surface need only be determined when the suitability of the chosen luminaire is checked. The authors have used "flux functions" and also the "P" charts determined by Zijl to calculate the indirect com-

ponents and have compared the results with measured values in a model of the Entrance Hall example given in the paper, finding close agreement. Nevertheless these methods involve lengthy calculations and tables giving inter-reflection ratios for a wide range of conditions are needed if the work is to be done quickly and easily.

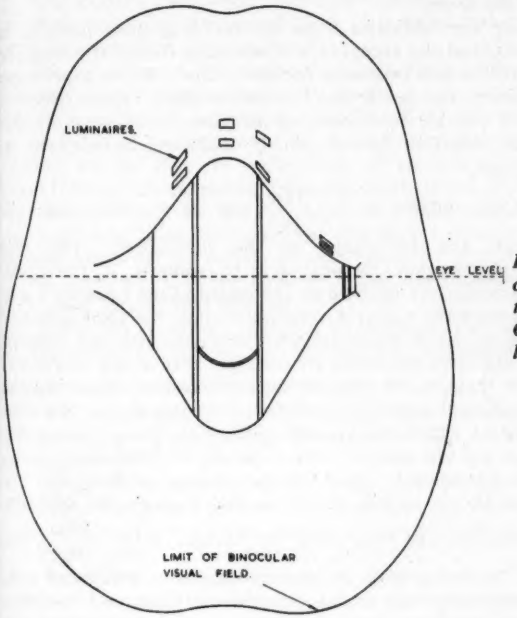

Fig. 9. Entrance hall interior plotted on a semi-sinusoidal projection for the determination of glare constant. Observation point on stairway gallery looking south.

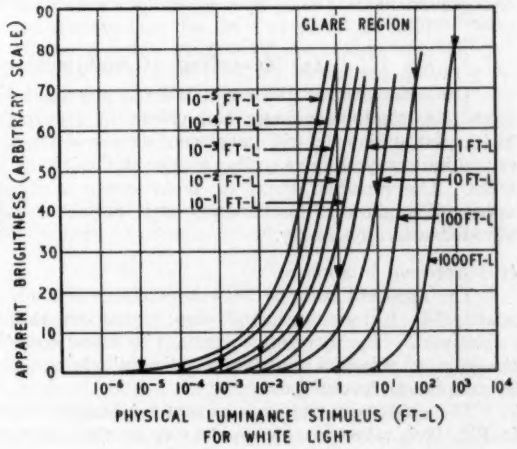

Fig. 10. Apparent brightness data. (Hopkinson, Stevens and Waldram, 1941).

(4·3) Choice and Location of Luminaires

Having obtained the illumination required at all surfaces or points of interest and the directions from which light should fall upon them, ideally it should be possible to build a pattern of light flux and to fix areas or points of common origin from which light should radiate, and thus decide upon the most suitable light source, its form of light control and its location in the room.

This approach, i.e., designing the luminaire from a room brightness pattern, is not easily accomplished at present, and the acceptance of standard forms of luminaire or some modification of them will remain necessary for some time. From experience and by trial calculations, those which most nearly give the desired effect, can be selected. The illumination which they will provide from selected locations to all parts of the room is determined, and surface reflection factors can, if necessary, be adjusted to give the specified luminance values.

Hopkinson's modified glare formula[14] $K = \frac{B_s^2\omega}{B_b}$ can be used to assist in determining the acceptable size and luminance of the luminaires. In this formula K is the glare constant, B_s the source luminance in ft.-lamberts, B_b the background luminance in ft.-lamberts and ω the solid angle subtended at the observer's eye by the glare source. B_b and K can have specified values and since the total quantity of luminous flux required within the room has been determined, the size and type of light source can be chosen. The unknown quantities are the luminance of the luminaires and the solid angle subtended by them at the observation point chosen for fixing the glare rating. The observation point will generally be chosen from one of the positions that are frequently occupied and at which the greatest glare will occur. Using the method described by Petherbridge and Longmore[15] the room can be drawn on a semi-sinusoidal (cylindrical) projection (modified to allow for glare source position) and the proposed luminaires drawn in as shown in Fig. 9. From this diagram the effective luminaire solid angles can be measured and then using the formula $K = \frac{B_s^2\omega}{B_b}$, the value of B_s can be determined. The value of B_s so determined can be compared with the specified luminaire background luminance to ensure satisfactory source luminance grading. The luminaire size and luminance can be adjusted and modified when the values obtained present difficulties for the manufacture of the luminaire. Additional background lighting may be required to ensure comfort.

(5) Revealing of Architecture and Form

The character of the room will be governed by the relationships between the modelling, shadows, texture and colour of the surfaces and contents of the room. Values of luminance will have been chosen to fulfil various purposes, but in themselves these may not give a clear picture of the interior as the eye and brain will interpret them. The possible effects of simultaneous contrast, of brightness constancy, and apparent brightness (luminosity), must be checked and luminance values must be adjusted where necessary.

(5·1) Apparent Brightness

The apparent contrast between surfaces depends upon the level to which the eye is adapted. It does not, for all adaptation levels, vary with the luminance (photometric brightness). It is therefore important to know something of the relationship between the physical stimulus and the resulting difference in apparent brightness for a range of adaptation levels[16].

The published data on apparent brightness[17] (from which the graph reproduced in Fig. 10 is taken) can be used to assess the order of contrasts and enable a general

assessment of the proposed lighting to be made. In making these assessments the relative sizes and positions of contrasting areas must be considered.

A further use of this data is for checking the luminance values selected for areas where local lighting is to be provided, to ensure that the order of contrast required, when general lighting is superimposed, is not unduly changed. The addition of general lighting equally over object surfaces having a given contrast can either increase or decrease contrasts, depending upon their reflectivities and luminance values, and the level of adaptation.

If, for example, two surfaces, one having a reflection factor of 0.5 and another of 0.1, are equally illuminated at 10 lm/ft² in an adapting field of 10 ft.-lamberts, the apparent brightness difference (Fig. 10) will be 26 − 11 = 15 arbitrary units. If the illumination is now increased by an additional 10 lm/ft² the apparent brightness difference will be 42 − 18 = 24 units, an increase in apparent contrast. On the other hand if two surfaces having the same reflectivity of 0.5, are illuminated, one at 10 lm/ft² and the other at 2 lm/ft², they have the same luminances as in the first case, and the apparent brightness difference will also be the same, i.e., 15 units. If the illumination is now increased by adding at each surface 10 lm/ft², corresponding to the change in the first case, then the apparent brightness difference will be 42 − 30 = 12 units, a decrease in apparent contrast.

Generally, contrasts obtained by differences in reflectivity increase, and those due to differences in illumination decrease with additional general illumination.

(5.2) Modelling, Shadow and Texture

The preferred form of modelling for general and for special areas will be governed by the particular design, and guidance for this can be obtained from published data of studies[12][18].

Since the quantities of the direct and diffuse components in an interior will determine the form of modelling at object surfaces, the Building Research Station in their studies of day-lighting have used the relationship between the direct and indirect "daylight factor" as an index of modelling.

In artificially lit interiors with sources on the ceiling there is evidence[19] that the ratio of the total illumination to direct illumination remains nearly constant for horizontal surfaces at work plane or floor level, but for vertical surfaces, i.e., the walls, the ratio may have a different value.

In the same way that the Building Research Station[20] has used the ratio of direct to indirect daylight factor we suggest that the ratio of direct to indirect components of artificial illumination affords a ready method of expressing modelling.

The density of shadows will be affected not only by the direct and diffuse components of illumination but by the relative sizes of objects casting the shadows and the sources themselves. A large array of relatively small sources of light distributed over a ceiling will produce a large number of confused shadows falling in many directions, whereas a directional flow of light will produce shadows cast mainly in one direction.

The light flux distribution for modelling and shadows are to some extent interdependent, but modelling will be influenced to a lesser extent by relatively small bright sources than will shadows.

(5.3) Colour and Decoration

The appearance of a surface is dependent not only upon its colour and reflectivity, but on the quantity and spectral composition of the light falling upon it. Two neutral grey surfaces of equal reflectivity can be made to appear quite different by allowing more light to fall upon one than upon the other. In a similar way the appearance of coloured surfaces are changed when varying amounts of light fall upon them.

The inter-reflection of light in an interior also affects the colour of the reflected

Table III
Installation Data

GENERAL LIGHTING

Luminaires: 15—Recessed modules 24 in. × 24 in. with 4 2-ft. 40-watt fluorescent lamps fitted with polystyrene louvres. Upward lighting to ceiling from above entrance lobby 4 5-ft. 80-watt fluorescent lamps with stove enamelled reflectors, cut-off arranged to avoid lamps being seen from stairway gallery.

Luminance

Calculated values.

Location	Illumination (lm/ft^2) Direct	Indirect	Final luminance ft.-lamberts
Floor	8	2.3	3
North Wall	4	3	5
E & W Walls	2.5	2.3	2
Ceiling	3	1.5	3
Gallery floor	14	4	5.5

SECONDARY LIGHTING

Wall Unit for accent lighting. Special design DRG No. RL.355 8 ft. × 8 ft. × 1 ft. 6 in., with 3 5-ft. 80-watt fluorescent lamps. Diagonally louvred. Louvres at 30 deg. to front surface.

RECEPTION DESK 2—Special design 'Diabolo' type spun aluminium reflectors with 100-watt incandescent lamps mounted on side of stairway.

ENTRANCE LOBBY 4—Recessed weatherproof fittings with 100-watt incandescent lamps.

NORTH WALL 4—Fittings of same design as at reception desk. Mounted one on each stanchion, at 6 ft. 6 in. above floor.

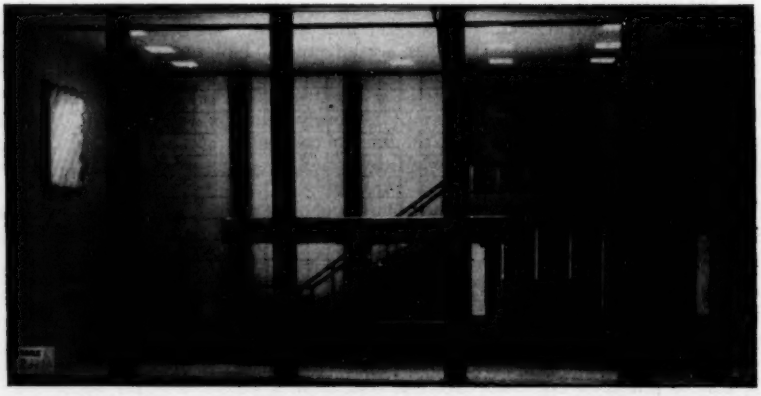

Fig. 11. Model of entrance hall used for photometric and apparent brightness checks. (Scale ½ in. to 1 ft.)

light as well as its brightness. The colour of light reflected from coloured walls within a room is more saturated than that of a flat sample similarly painted and viewed in neutral surroundings. This is due to a change in the spectral composition of the light caused by repeated reflections at selectively absorbing surfaces. Specular reflections from glazed surfaces take on the colour of the source whatever the background colour.

The specification of colour is complex, but the simplest method of specifying colours for surface finishes is probably the Munsell system in which colours are graded according to hue, value and chroma.

Having established the luminance values and reflection factors of room surfaces and the means of illuminating them, surface colours can be chosen. Using the Munsel colour system, the hue and chroma having the required reflection factor can be selected. Where from consideration of illumination alone, a large area has been specified as requiring the same reflection factor throughout, monotony can be avoided and contrast introduced by using different hues. Alternatively, a small area of high chroma can be set in contrast with a larger area of low chroma and contrasting hue. Many variations are possible and in this way the colour scheme can be related to the needs of good lighting, comfort and aesthetics[21].

(6) Installation Data

When all the data required for the specification have been assembled, a number of checks should be made of illumination and luminance values to ensure that contrasts are of the right order, that the discomfort glare rating is satisfactory and that luminance grading around the task allows for satisfactory visual performance. Checks can be made so that glare from reflected light is not a source of distraction. Installation data can then be recorded, for example, as shown in Table III, where part of the data used in the Entrance Hall example is given.

The subjective appraisal of a design can be made with the aid of scale models; photometric measurements can be made in them to check illumination and luminance values. Reflection factors of surfaces and the choice of colours can be checked and when necessary adjusted. Modelling and contrast grading can also be appraised. The building of models and model fittings frequently present difficulties, but detailed structure can be omitted provided the distribution of light is correct. For completely reliable subjective appraisals, large-scale models containing furniture and other details are essential for the observation and assessment of an interior[18]. Small models, however, are a help. The lighting design for the Entrance Hall used for the example in Tables I, II and III and Figs. 6, 7 and 8 was aided by the small model shown in Fig. 11, made to a scale of $\frac{1}{2}$ in. to 1 ft.

(7) Trends

The many factors involved in an all-embracing design method are complex and often difficult to determine with certainty. There is still much to be learned, tried and tested, but the approach, beginning with the architect's plan and leading to the engineer's pattern of brightness and contrast from which the quantity and direction of light flux to all parts of the interior can be determined, presents a more logical and comprehensive attack than that of earlier methods. A number of the factors which have to be determined frequently involve lengthy calculations, but as this approach becomes more widely used, quicker methods of acceptable accuracy will undoubtedly be devised and introduced, saving time and effort.

It should stimulate the design and use of new types of luminaires which are more suited to the requirements of good lighting and have formal qualities which are more acceptable than many at present in use.

There must be an identity of aim between architect and lighting engineer if lighting is to be applied successfully; the method of approach described in the paper should help to achieve this.

Acknowledgments

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Discussion

MR. J. REID: It is going to be difficult for me to open the discussion because I have been sitting here thinking that everything I have been hearing and seeing tonight, I have heard and seen before.

The methods which have been described seem to be very similar to those which were being put forward not so long ago in this very room by Mr. Waldram, and most of the demonstrations are also well-known.

The authors suggest that when trying to determine the desirable brightness patterns for an interior, perspective drawings should be used, and they have shown us three examples. Now there is nothing new in this and architects have used perspective sketches for years, not the elaborate and laboriously drawn sort that we have seen tonight but scruffy little scribbles around the edges of their drawing boards! Many of the lighting engineers present must have visited architects' offices and seen the sort of thing I mean and if they think about it, I am sure they will all agree that scruffy though the scribbles may have been, they all had something in common; areas were shaded and walls, floors and ceilings appeared as black or in tones of grey, which means that the architect was thinking in terms of light and shade. If you ask an architect about "desirable brightness patterns" he will probably look rather blankly at you, but say "light and shade" and he will know what you are talking about.

It seems to me that the main danger of the methods described is that they, by their slow and laborious nature, will kill all the excitement and interest that a scheme may have long before the calculations are complete. Tonight, the authors have shown us a classic example of this. They chose an entrance hall and proceeded to show us how it should be lit. Now, an entrance hall is a place where people do not stay for any

great length of time, but rather move through fairly rapidly, and use its staircase. What an opportunity for a dramatic lighting scheme, for shade and sparkle which would not be suitable for the office or works areas that lie behind, and just see how that chance has been missed!

We must all watch that papers such as the one we have heard tonight do not lead us into the use of methods that will almost inevitably produce monotonous schemes.

Lighting engineers must not be allowed to think that a slide-rule and a set of tables, no matter how good they may be, are a substitute for a lively imagination and perceptive eye. In industriously ironing out the trouble spots of our lighting schemes, we must not become guilty of "throwing the baby away with the bath water."

MR. J. M. WALDRAM: I welcome this paper as a further item in the development of the idea of the Design of the Visual Field. It will perhaps be recalled that this principle was first suggested in a report of a Committee of the National Illumination Committee, and that practical methods of design on this basis were first suggested in my papers, read to this Society in January, 1954, and to the C.I.E. in Zürich in 1955. In those papers the hope was expressed that others would try this method of design, and it is a matter of satisfaction that the authors have done so; even though their paper does not go further than the earlier papers it is good to have confirmation of the findings and acceptance of the principles.

Mr. Reid has stressed the relationship of the lighting engineer to the architect, and it is perhaps worth recalling that this method of design regularises the functions of the lighting engineer and the architect in a very interesting way. In lighting, as in most other technical features of a building, the engineer has, ideally, first to establish the limits which must be observed for safety and convenience. This has already been done by means of the I.E.S. Code; it is one among many such Codes, produced by engineers, which establish the limits within which the architect must work, if his building is to be safe and habitable. Then, ideally, it is for the architect working within these limits to conceive and design the appearance which he desires, as an aesthetic creation. Then the engineer comes in again, to design the installation which will realise the architect's conception. In practice, of course, it is less simple; there are limitations on where lighting equipment can be put, and upon how closely the architect's ideas can be followed, and the engineer has to work with the architect and watch his ideas grow, and the building take shape under his fingers, accepting the need to modify and scrap earlier ideas until a workable compromise can be achieved. It is exciting, and as Mr. Reid says, it is great fun. One unexpected consequence is that once the desired aesthetic result has been defined, one becomes far more an engineer than before, using almost every trick, both of calculation and of practice, to obtain the result. I believe that this approach, which the authors have also followed, will give us a workable bridge between the two professions, and I have great hopes for it.

On two points of detail: I am glad to note the authors' use of perspective diagrams. They should, however, be drawn from the user's viewpoint, not for a viewpoint outside the interior as the authors have done, which is of little use and probably misleading. I deplore, however, the proposal to use scale models for solving these problems except in very special cases. They are expensive and difficult to use, and the whole point of the newer methods of calculation is to avoid the use of models and trial installations. Models may be practicable in very simple cases, with idealised lighting equipment such as flat diffusing panels; but it would be very difficult and expensive to produce them for most of the interiors with which I have been concerned.

MR. E. R. HARRISON-JONES: To me this paper is analogous to the Borough Engineer being his own architect, in the sense that the Architects Department has the minority

role of dressing up the engineer's designs. The results of this approach can, unfortunately, be seen on all sides.

In the example to-night we have a typical pure engineering solution to a largely aesthetic problem.

The engineers sincerely believe that they have produced the perfect engineering answer. Maybe they have, but they have also produced an extremely uninteresting interior, totally lacking in imagination, devoid of character. A Borough Engineer's dream in fact!

The true practice of lighting demands a combination of art and engineering. Amongst many things, sensitivity of function, scale, mass and a sense of drama are vital ingredients to the lighting of an interior, particularly of this nature.

Any good architect, or lighting engineer, would have produced a lighting system for this interior sympathetic to its function, and in a very small fraction of the time, by instinct, although the lighting engineer will check by calculation afterwards. But you cannot replace instinct with a slide-rule.

Work of this nature makes a useful contribution to lighting engineering but not to the lighting art.

MR. R. L. C. TATE: There are architects and architects. . . . Some are exceptional men with lively minds, who can visualise the effects they want to create, but others are dull and unimaginative and not really architects at all—they could be better described as "co-ordinators of building materials."

The lighting engineer has to deal with both kinds, but if the architect designs a poor building, he is likely to get a dull lighting scheme. I feel that most of Mr. Reid's criticism was directed at the very uninteresting building represented by the model. I don't know who the architect was, but he was obviously a stick-in-the-mud. The lighting engineer cannot be expected to turn a bad building into a good one. After all, the title of the paper is "Artificial Lighting as an Aid to"—not as a substitute for—"Architecture."

MR. H. HEWITT: In view of the remarks already made, I am beginning to feel rather sorry for the authors, and I feel that we ought to pause to pay tribute to those workers (including the authors of this paper) who have in recent years investigated the more qualitative factors in lighting. They have persistently reminded us that lumens are not everything and I am sure that their work has already, to some extent, improved standards of lighting. But not necessarily by the painstaking processes suggested in this and other papers. Mr. Penny has recently reminded us in his "Random Review" (*Light and Lighting*, January, 1957) that a number of schemes have been planned along these lines but none has yet been installed. This is not difficult to explain as these processes need a rare combination of circumstances before they can easily be employed.

Firstly, there must be active co-operation between the lighting engineer and the architect (or more specifically the interior decorator) *at the right time*. Secondly, there must not be too severe an economic limit. Then there should preferably be a fairly constant visual task involving a single viewpoint, or one viewpoint that is predominantly important. Finally, we need a lighting engineer who is something of a mathematical genius and who is prepared to integrate himself into the ground to analyse a picture in his mind's eye, which should be almost a work of art. I say "should be" for this is the chief difficulty; we must know what we want.

Perhaps the most significant thing about this present paper is that it starts by asking for a good deal of initial insight, and finishes up by using scale models. All that lies in between is extremely important but is difficult to regularise, and it could be that too great an emphasis is being placed on this middle section and too little on the beginning and end.

I do not doubt the usefulness of papers such as this, but I am concerned about

the effects of all these writings on the younger lighting engineers who are growing up, I am convinced, that the future of good lighting depends more upon men of imagination with an experimental turn of mind than upon the draughtsmen who can also use a slide-rule. It is the old problem of inspiration and technique : and at the moment I am afraid that technique is running away with us.

MR. D. PHILLIPS: I should like first to endorse Mr. Tate's remarks concerning the views of the opening speaker. Mr. John Reid is by no means a typical architect; he lectures to architects and lighting engineers on lighting and has a real appreciation of this subject; his remarks therefore by no means represent architectural opinion, since the majority of architects know very little about lighting.

The bulk of the previous speakers have enjoyed themselves at the expense of the authors, and this helps to make a lively meeting, but very little of a constructive nature has been said. Of course, methods of analysis are tiresome to the intuitive designer, and in my view are generally only applied after the design has been envisaged, more as a check like rules of proportion, but this does not make them any the less valuable. I entirely agree with the way in which the authors have analysed the problems of lighting in buildings into two parts:—

1. The purpose of the building . . . lighting for use and safety, which deals with lighting as experienced through the senses, and
2. The building itself . . . the impression of the impact of the purpose of a building on the mind, or the way in which the building is appreciated through man's intellect.

This would take into account the architectural principles of unity, variety and significance. This seems to me a most useful analysis so long as it is realised that the two are closely dependent upon each other, since generally the same lighting equipment performs both functions. There are architectural programmes which deal specifically with man's emotional needs, such as cinemas, theatres and restaurants, and here the second aspect would be of primary importance; but by far the bulk of the work of the architect is concerned with buildings in which the lighting equipment should be an anonymous part of the building structure. In these cases the first aspect would play the more important role, the second ensuring that the equipment integrates with the other building components in an ordered manner to achieve a unified form.

The paper brings out the need for standardisation of lighting elements and makes the point that specially designed equipment is inevitably more costly to produce and install. I am wondering what the authors mean by "elements" here, for if they mean complete fittings, as we know them, this is in fact a doubtful blessing. If, however, they mean the production of simple component parts consisting of lamps and reflectors, which can be related to the structure of a building, either on their own or in relationship to standard forms of louvres and diffusers, this is certainly a trend which should be encouraged. This type of development includes forms of louvred ceilings, luminating ceilings and forms of simple boxes containing light sources which integrate with other standard building components, and which should be capable of mass production quite cheaply. With these tools at the hands of the architect, it should be possible for him to think of the building form itself as its own luminaire. This concept has already been applied in certain buildings such as the shell concrete lighting at Brynmaur Rubber Factory, the cold cathode lighting in the drawing office of C. A. Parsons, Newcastle-upon-Tyne, used with curved ceiling panels, and the reinforced concrete louvred structure designed for a foundry by John Bickerdyke whilst at the Building Research Station. It is possible to satisfy the needs of man from the aspect of his senses and his intellect in this manner.

The Royal Festival Hall shows that solutions of this character have a decorative

effect without any recourse to the addition of fussy details, and where the lighting is worked out at an early stage in the design process there is no need for increased cost.

I was sorry to see that there was no reference in the paper to the night appearance of the building seen from outside. This obviously involves illumination levels, and colour and position of sources, which must be balanced to achieve an effective composition at night. Although this may not affect the man in the building, it is of overriding importance from outside where large areas of plate glass are used, as the harmony and order of the building can be completely disorganised by inappropriate lighting. The new T.U.C. building, where the whole of the ground floor on one side is plate glass, is an object lesson for all who see it, for at present temporary lighting has been installed with bare lamps, and the effect at night is of complete visual chaos. It will be interesting to see, when the final lighting scheme has been installed, whether the building succeeds in this respect or not.

MR. F. BENTHAM: I feel that in the search for an exact, planned approach to lighting we may neglect the freedom which is the essence of light. The wonder of electric light is a bulb mobile on the end of a flex. Light which has to be so exactly designed because it is going to be used in such a way that it cannot be changed is light imprisoned and entombed. Perhaps, after all, the hanging fitting and/or floor standard are more truly electric light than solid, built in coves, laylights, buried wiring and so forth.

As regards all this talk of co-operation with the architect, I have always felt that the best approach was war. Co-operation spells design by committee—the way to mediocrity.

MR. P. A. JAY: Mr. Waldram has said that the relationship between the lighting engineer and the architect is the same as that between any other engineer and the architect. While this may be true of some lighting engineers and some architects, in general the practising engineer knows that the architect looks to him for intelligent suggestions, and if his suggestions, however well founded technically, are architecturally fatuous, that engineer will rarely be approached a second time. Therefore, despite the many discussions which have taken place at recent meetings of the Society on the desirability or otherwise of the lighting engineer having some architectural knowledge, events have rather tended to overtake the Society, and the successful lighting engineer must know rather more about architecture and, since time is limited, probably knows less about the more recondite technical aspects of lighting than is often suggested.

In this connection, there seems to be a widening gulf between the research worker and the practising engineer. We feel ourselves very much in the position of the Egyptian surveyors, who knew that they could construct a right angle by dividing a rope into lengths in the ratio three to four to five many years before Pythagoras proved that this must be so. They had, of course, no reason to sneer at Pythagoras, but there are too many papers which develop a cumbersome mathematical technique for obtaining results no better, and in some cases worse, than have been obtained in the past by a combination of experience, intuition and common sense.

I do not wish to suggest that this work is not valuable, but only that it has not yet reached the point of enabling us to do anything that we cannot already do, nor even to help us to do it more quickly or reliably. Perhaps I am objecting only to the title of the paper, against which, had it been called "A Theoretical Consideration of Some Aspects of Lighting Design," I could have had no complaint.

All the same, I think that there might well be some research devoted to answering the sort of questions that architects do ask, and the research worker should try to find out what these questions are. At present he seems concerned to find answers to questions that only he himself would ever dream of asking, and the areas of contact between theory and practice are therefore very limited.

MR. A. G. PENNY: The authors refer to the necessity to consider the client's own special needs and for the planning of the lighting to be done quickly and easily. I agree with them on these points, but feel that they have not stressed their importance sufficiently. In the example with which they have chosen to illustrate their paper they have apparently ignored both factors.

The authors appear to have decided that the entrance hall of a large office block is the entrance to an imposing building (perhaps a government building in Whitehall) having considerable prestige value for which out-of-the-ordinary lighting would be justified. It might, however, be only the entrance to the clerical departments of a commercial firm, used mainly by the employees, and not therefore calling for the special treatment which they have decided to give it. There ought to be some indication in their data sheet as to what standard is to be applied.

As regards the problem of providing the lighting plan quickly and easily, I feel that the urgent need is for a system which will produce reasonably good results within the ordinary compass of planning costs. The normal fee of an architect is 6 per cent. of the total building cost. It is reasonable to suggest, therefore, that the cost of planning a lighting scheme should not be more than 6 per cent. of the cost of the lighting installation. I would estimate that the scheme evolved by the authors for their entrance hall would cost the client in all some £500. Therefore, out of 6 per cent. of this—£30 has to provide the whole scheme, from the choice of luminaires to the wiring plan. I doubt if this sum would suffice for the technique described by the authors. And if they had to tackle an ordinary installation for an ordinary entrance hall the fee would have been nearer £5 than £30. To-day this would hardly provide the wiring plan let alone any consideration of luminance and contrast patterns.

The general overall conception of a lighting scheme ought to stem from the imagination of the artist. If the lighting engineer can be provided with a simple, mechanical means of converting the architect's *broad* ideas into a preliminary plan of lighting, there would be ample opportunity for both to display their skill and yet, at the same time, it would provide a confirmatory check on their plans and thus avoid the horrid mistakes which are made to-day even by competent architects and engineers.

MR. H. G. JENKINS: I think the authors have been singularly unfortunate in their opening speakers: Mr. Reid complained that there was nothing new in what the authors had to say, and Mr. Waldram was largely of the same opinion. It cannot be expected that all papers presented to the Society should be full of new and original material: in the present paper the authors have dealt effectively with their subject and accompanied their remarks with lantern slides and demonstrations. We ought to be grateful to them for the considerable trouble they have taken.

DR. R. G. HOPKINSON: I would like to support what Mr. Penny has said, and I hope that the authors have not taken too seriously the criticism by the opening speakers. This paper is one of a succession of papers on a rapidly developing subject, which are part of the general pattern of lighting research as we know it to-day. It was said earlier that there is nothing original in this paper. Nevertheless, I think that the authors have succeeded in making their subject clear to the average lighting engineer and architect, and we are continuingly crying out for simplification of just this kind to be undertaken. It is a pity that, when we get it, we dismiss it as lacking in originality. The authors have selected what they consider to be the best of previous contributions and by means of simple worked example they have taken us through the basic principles and demonstrated how these lighting principles can be applied in practice to achieve the complete finished result. Claims for priority

were made in the discussion. Even earlier claims might be made on sound documentary evidence but they would serve little purpose; it is the future and not the past of the subject which should interest us.

I support the authors in another matter, too, that of the use of models for lighting research. I fully admit that the brilliant architect or lighting engineer may be able to do without models, because he can visualise the final result. But for the general run of architects and lighting engineers who have jobs of work to do, the model technique, when properly applied, can be of the very greatest value. It need not be laborious nor time-consuming. We have developed, at the Building Research Station, a simple "modular" system of model building which enables us to produce a model of quite a complicated layout very quickly indeed. On one particular occasion the need for a quick solution to a complicated lighting problem was stated mid-morning; by lunch-time the model had been erected in full detail, the photometric measurements and the subjective judgments all made, and the preliminary detailed report written and sent off to Trinidad by the end of the day. This was not a simple lighting problem, it involved complicated integration of light in outer verandas, etc., and demanded appraisals of glare and of lighting character. A solution by purely computational methods could not have been found in the time. The use of models in lighting research is not antiquated, it has a great future before it. Admittedly we were able to work at this speed only because we had years of experience of both the photometric problems involved, and also of the glare, apparent brightness and contrast problems which the complicated layout of the building necessarily raised. This is, however, as it should be; the basic principles must be absorbed the hard way until they are thoroughly understood, and then the actual solution to the specific problem should be undertaken by the most expeditious and simple method available.

(Communicated.) When the above remarks were made in the discussion I did not have the preprint of the paper in front of me. I have asked for a correction of the formula given in section 4.3, which was incorrect in the preprint. I understand that the correction has now been made for the final publication.

I would also have liked to have asked the authors what is their experience of the use of the Split-Flux method for the estimation of the indirect component of the illumination in an artificially lit interior. This method was originally designed for the computation of the indirect component of interior daylight, but experience has suggested that it is quite a useful method for a first-order appraisal for artificial lighting as well. We have used it at B.R.S., and other groups who are working in co-operation with us have also used it with some success.

MR. J. MUSGROVE (written contribution): I have been actively engaged as an architect in collaborative studies with lighting technicians for some years. The value of these studies has never been doubted by any of us who have taken part in them. I welcome this paper because it extends this kind of collaboration outside the research and development fields and into everyday design practice. Every attempt to explore the common ground between the intuitive approach of the architect and the factual one of the engineer or technician is worth careful consideration by both disciplines.

I believe, however, that the authors err in that they over-simplify the analysis of the design process. The complex psychophysical experience resulting from visual perception in an enclosed space cannot be reduced by the architect to a set of "basic requirements." The common vocabulary for such a process is at present lacking, but *can* be developed in collaborative studies which, at first, will have to be designed to explore the "dark region" between elucidation of the physical variables (by the engineer) and the aesthetic assessments of the architect. I submit that the sort of bi-partite design process described in the paper, in which the engineer realises

"character" by interpreting the architect's requirements is extremely difficult, if not actually dangerous, at present, because the architect cannot describe character in terms of requirements. Model studies are, however, the essential meeting ground, because they enable the architect to exemplify rather than describe his ideas, while at the same time allowing the lighting engineer to study the physical variables and to give direction to the architect's thinking about choice and disposition of fittings. At present, a collaborative model study must, however, be in the nature of a single process, until all the factors are integrated in the minds of both engineer and architect. When this is achieved, the engineer will be able to give direction and guidance to the architect without infringing his prerogative of aesthetic choice.

Valuable work is being done in this field by the Building Research Station in collaboration with architectural research groups such as the Nuffield Foundation Division for Architectural Studies. The early results of this work are being tried out in practice, and further work grows out of this experience; the common ground is gradually being explored. The process cannot be hurried—but every contribution such as the one described in this paper is valuable, and will contribute towards the better understanding of useful techniques which neither discipline can afford to neglect.

May I, then, emphasise my support of the authors in their use of models for interior design studies. Model studies need not be time-consuming, expensive or elaborate. A model has recently been designed and used in lighting studies at the Building Research Station, and it merely consists of small standard units with which almost any model room can be constructed quite quickly: the units are stored flat when not in use. In the work cited above, models have been found indispensable. The architectural approach is visual—and it is always easier to demonstrate than to describe, even with the aid of perspective sketches.

THE AUTHORS (in reply): Three main points are raised by Mr. Reid and several speakers. These suggest that the analysis of the design process is over-simplified, that the lighting calculations are too complex, and that the cost of models generally prohibits their use. We agree that in the necessary condensation for the paper it is not possible to cover in detail all aspects of design, and certainly we have nowhere suggested that the slide-rule can be a substitute for inspiration.

The comparison in the paper of alternative methods for the more complex lighting calculations may have increased their apparent difficulty, but any one method selected is still laborious and we have stressed the need for simpler and quicker methods of acceptable accuracy; much work is going ahead in our own and other laboratories to try to develop these. Because of the complexity of the calculations, we repeat that simple models may save both time and money. For lighting problems, these certainly need not be elaborate as is shown by Fig. 11.

Similarly, perspective drawings may, of course, be in the form of sketches—but we wonder if Mr. Reid has tried submitting "scruffy" sketches to editors for reproduction. The simple outlines we used will generally be supplemented by many sketches which may be shaded, but the light and shade in these will have to be interpreted by the lighting engineer into the measurable quantities of brightness (luminance) which can then be contrived.

Mr. Waldram, while welcoming the paper, seems concerned because no entirely new and original work is included. This, we feel, is inevitable because of the time necessary to introduce into practical designs the ideas set out in the 1954 N.I.C. report, "Design for the Visual Field." Our references were compiled to acknowledge the efforts of the many workers who have contributed, often working independently along similar lines—as is shown, for example, by references 12, 17, 19 and 20.

The example used was not chosen, as suggested by Mr. Harrison-Jones, because we considered it the perfect engineering answer to the problem, but in order to make

the analysis with as simple a subject as possible. We were not concerned with a critical analysis of its architecture—although we would add that dignity rather than display was the guiding motive. Critical examination of an architectural design cannot be undertaken unless all the environmental factors are included—we feel that Mr. Tate has been a little harsh.

While agreeing with Mr. Hewitt that there is a danger of over-emphasis on what he refers to as "the middle section of a design," there is rather greater danger of its being neglected because of the work involved. The use of full-scale models was not mentioned and is rarely necessary.

Mr. Phillips has said that methods of analysis are generally only applied after the design has been envisaged. This must be so; at least until the broad outlines have been settled. The analysis and calculations lead to a determination of the most suitable light source, and of the modifications necessary to its intrinsic light distribution and luminance to provide the pattern of light and shade and contrast and colour. By "standard elements" we mean standard forms of light control units such as diffusers, louvres, refractors or reflectors which can be applied in a variety of forms either in separate "fittings" or as an integral part of the building. While, ideally, an architect would probably prefer individually designed equipment to give him the greatest possible freedom, units which can be built into many forms provide an economic compromise. This should help to satisfy Mr. Bentham's plea for flexibility.

Mr. Jay is concerned with the gap between theory and practice. One of our aims in presenting this paper was to try to help bridge this gap by promoting discussion on points of common interest so that "the questions that architects do ask" may be answered more effectively.

In reply to Mr. Penny we agree that the client's own special needs can well be included in the data sheets. Each engineer will develop his own method of recording data—our data sheets were included to help him do this. We thank Mr. Jenkins for his appreciation of our illustrations; his other comments are covered by our reply to Mr. Waldram.

Dr. Hopkinson has welcomed our attempt at simplification and ably summarised what we had set out to do. We were pleased to have his support for the use of simple models. Like Dr. Hopkinson we did not see the preprint until we had presented the paper and the printer's error in the glare formula has been corrected. We have applied the Split-Flux method, comparing it with other methods for a small number of examples of artificially lit interiors. We agree that it does provide a useful method for first order appraisal.

We appreciate Mr. Musgrove's written contribution; in the opening of our reply we have covered the points concerning over-simplification of the analysis of the design process.

The describing and interpreting of character is indeed most difficult, and we note his warning that some of our suggestions should not be used without careful consideration and that he finds collaborative model studies valuable in this respect.

The lively discussion has well repaid our efforts in compiling the paper. Of course, flexibility of approach in consultation between architect and lighting engineer is essential for progress in the art and science of lighting. We hope that the analysis of the problem we have given will aid that interpretation by lighting engineers of an architect's conception, which is an essential complement to inspiration for the achievement of success.

Additions to the List of Members

The following applicants have been duly elected by the Council to membership in the Society and their names have been added to the list of membership:—

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